Before global warming, was the Earth cooling down or heating up?

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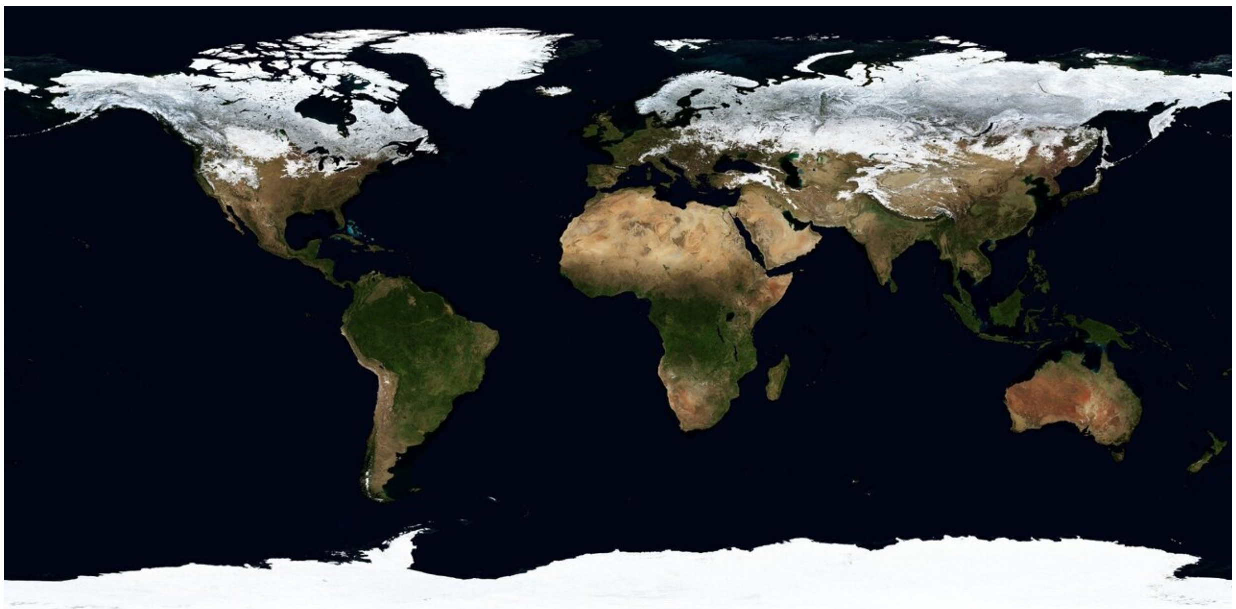

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Accurate climate models play a critical role in climate science and policy, helping to inform policy- and decision-makers throughout the world as they consider ways to slow the deadly effects of a warming planet and to adapt to changes already in progress.

To test their accuracy, models are programmed to simulate past climate to see if they agree with the geologic evidence. The model simulations can conflict with the evidence. How can we know which is correct?

A review article published today in *Nature* addresses this conflict between models and evidence, known as the Holocene global temperature conundrum.

Lead author Darrell Kaufman, a Regents' professor in the School of Earth and Sustainability, and University of Arizona postdoctoral researcher Ellie Broadman, a co-author who worked on this study while earning her Ph.D. at NAU, analyzed a broad swath of available data from the last 12,000 years to break down the problem.

The study builds on work Kaufman did that was included in the latest major climate report by the Intergovernmental Panel on Climate Change (IPCC) and looks at whether the global average temperature 6,500 years ago was warmer, as indicated by proxy evidence from natural archives of past climate information, or colder, as simulated by models, in comparison to the late 19th century, when the Industrial Revolution led to a significant increase in human-caused warming.

This comprehensive assessment concludes that the global average temperature about 6,500 years ago was likely warmer and was followed by a multi-millennial cooling trend that ended in the 1800s. But, they cautioned, uncertainty still exists despite recent studies that claimed to have resolved the conundrum.

"Quantifying the average temperature of the earth during the past, when some places were warming while others were cooling, is challenging, and more research is needed to firmly resolve the conundrum," Kaufman said.

"But tracing changes in global average temperature is important because it's the same metric used to gauge the march of human-caused warming and to identify internationally negotiated targets to limit it. In particular, our review revealed how surprisingly little we know about slow-moving climate variability, including forces now set into motion by humans that will play out as sea level rises and permafrost thaws over coming millennia."

What we know

We know more about the climate of the Holocene, which began after the last major ice age ended 12,000 years ago, than any other multi-millennial period. There are published studies from a variety of natural archives that store information about historical changes that occurred in the atmosphere, oceans, cryosphere and on land; studies that look at the forces that drove past climate changes, such as Earth's orbit, solar irradiance, volcanic eruptions and greenhouse gases; and climate model simulations that translate those forces into changing global temperatures. All these types of studies were included in this review.

The challenge up to now has been that our two significant lines of evidence point in opposite directions. Paleo-environmental "proxy" data, which includes evidence from oceans, lakes, and other natural archives, point to a peak global average temperature about 6,500 years ago and then a global cooling trend until humans started burning fossil fuels. Climate models generally show global average temperatures increasing in the last 6,500 years.

If the proxy data are correct, that points to deficiencies in the models and specifically suggests that climate feedbacks that can amplify global warming are underrepresented. If the climate models are correct, then the tools for reconstructing paleotemperatures need to be sharpened.

We also know that, whether the numbers trend up or down, the change in global average temperature in the past 6,500 years has been gradual—probably less than 1 degree Celsius (1.8 degrees Fahrenheit). This is less than the warming already measured in the last 100 years, most of which humans have caused. However, because global temperature change of any magnitude is significant, especially in response to changing greenhouse gases, knowing whether temperatures were higher or lower 6,500 years ago is important to our knowledge of the climate system and improving forecasts of future climate.

What we don't know

This study highlighted uncertainties in the climate models. If the authors' preferred interpretation—that recent global warming was preceded by 6,500 years of global cooling—is correct, then scientists' understanding of natural climate forcings and feedbacks, and how they are represented in models, needs improvement. If they're incorrect, then scientists need to improve their understanding of the temperature signal in proxy records and further develop analytical tools to capture these trends on a global scale.

Attempting to resolve the Holocene global temperature conundrum has been a priority for climate scientists in the last decade; Broadman remembers reading the initial paper on this topic when she started her Ph.D. in 2016. All the studies since have added to the understanding of this issue, which gets scientists in the field closer to a comprehensive understanding.

Recent studies on this topic have tried adjusting proxy data to account for their presumed weaknesses, inserting plausible forcings into climate models and blending proxy data with climate-model output, all arriving at different conclusions about the cause of the conundrum. This review takes a step back to revisit the issue with a comprehensive global-scale assessment, showing that we don't yet know the solution to this conundrum.

Developing widely applicable methods of quantifying past temperature is a high priority for climate scientists already. For example, Kaufman's lab is testing the use of chemical reactions involving amino acids preserved in lake sediment as a new method for studying past temperature changes. Combined with new radiocarbon dating technology from the Arizona Climate and Ecosystem lab at NAU, this technique could help determine whether global warming reversed a long-term cooling trend.

Why it matters

Broadman, whose work includes a focus on science communication, created the figures that accompany the research. This is a critical way of communicating hard-to-understand results to audiences—and in climate science, the audiences are diverse and include educators, policymakers, nonprofits and scientists throughout the world.

"One interesting takeaway is that our findings demonstrate the impact that regional changes can have on global average temperature. Environmental changes in some regions of the Earth, like declining Arctic sea ice or changing vegetation cover in what are now vast deserts, can cause feedbacks that influence the planet as a whole," Broadman said.

"With current global warming, we already see some regions changing very quickly. Our work highlights that some of those regional changes and feedbacks are really important to understand and capture in climate models."

Additionally, Kaufman said, accurately reconstructing the details of past temperature change offers insights into climate's response to various causes of both natural and anthropogenic climate change. The responses serve as benchmarks to test how well climate models simulate the Earth's climate system.

"Climate models are the only source of detailed quantitative climate predictions, so their fidelity is critical for planning the most effective strategies to mitigate and adapt to climate change," he said. "Our review suggests that climate models are underestimating important climate feedbacks that can amplify global warming."

More information: Darrell Kaufman, Revisiting the Holocene global temperature conundrum, *Nature* (2023). DOI: 10.1038/s41586-022-05536-w. www.nature.com/articles/s41586-022-05536-w

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